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Energy Confinement in Shaped TCV Plasmas with Electron Cyclotron Heating

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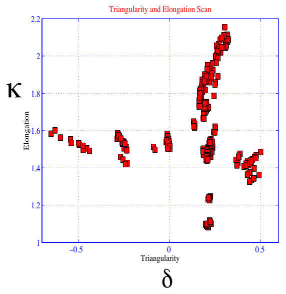
Confinement with ECRH

- Effects of plasma shape on electron energy confinement and central MHD activity
- Parameters varied:
  elongation κ, triangularity δ, ECH power P_{EC}, electron density n_e, plasma current I_p (q_{eng})
- present ECRH syst.em: 1.5 MW, 2 s : 3 gyrotrons at the second harmonic X-mode 82.7 GHz
  (soon extension to a total power of 3 MW X2 and 1.5 MW X3, 118 GHz)

Elongation and Triangularity Range, Experimental Characteristics

elongation κ - triangulartity δ - cross



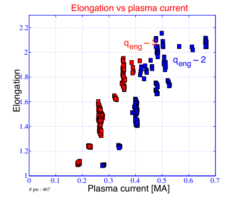
- $1.05 < \kappa < 2.15$ (2.58)
- $-0.65 < \delta < 0.5$

- $1.7 < \mathbf{q_{eng}} < 3$
  $(2.3 < \mathbf{q_a} < 6)$
  $190 < \mathbf{I_p} < 670$kA (1MA)
  q_{eng}=5abB/RIp

- Limiter L-mode discharges

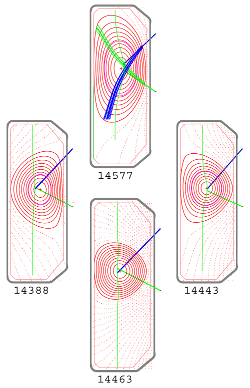
$R_o = 0.89$ m
$a = 0.25$ m
$B_o = 1.45$ T

in two q_{eng} - scans:



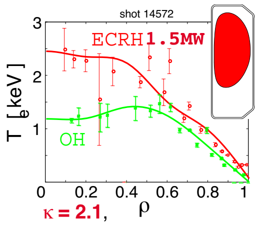
q_{eng} = constant scans to maintain self-similar profiles, i.e. constant q=1 radius, independently of shape:
(H. Weisen et al., PPCF **40** (1998) 1803)

Temperature Profiles for different Shapes



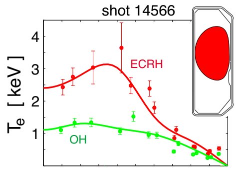
- 3 launchers (upper lateral and equator)
- **Power deposition inside inversion radius ρ_{inv}**
- $0.5\text{MW} \leq P_{EC} \leq 1.5$ MW
- $0.1\text{MW} < P_{OH} < 1$ MW
  (OH & EC-phases)
- $\sim 1 < P_{EC} / P_{OH\ (\text{during EC})} < \sim 10$

High elongation



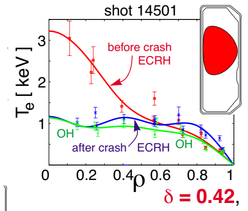
κ = 2.1,
δ = 0.3, q = 4.1,
$n_{eo} = 2.5 \times 10^{19}$ [m^{-3}]

Negative triangularity
Strong mode activity

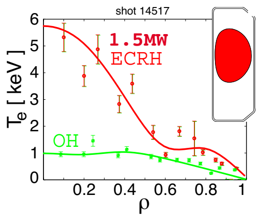


δ = - 0.26,
κ = 1.54, q = 4.0
$n_{eo} = 2.4 \times 10^{19}$ [m^{-3}]

Positive triangularity
Large Sawteeth



δ = 0.42,
κ = 1.42, q = 2.9
$n_{eo} = 2.7 \times 10^{19}$ [m^{-3}]

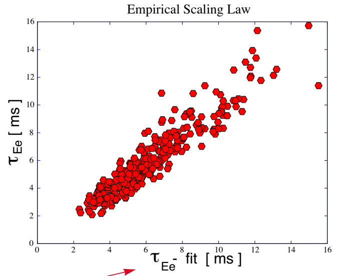


Moderate elongation

κ = 1.5,
δ = 0.2, q = 4.2,
$n_{eo} = 1.3 \times 10^{19}$ [m^{-3}]

Confinement Analysis

Multivariable Regression through the full κ-δ-scan

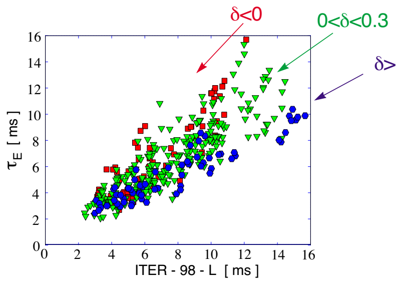


$$\tau_{Ee\ fit}[\text{ms}] = 2\times6^{\alpha_{Ip}}\, n_{e19}^{0.46}\, P^{-0.68}\, I_p^{\alpha_{Ip}}\, \kappa^{\alpha_\kappa}\, (1+\delta)^{-0.35}$$

$\alpha_n = 0.46\pm0.2$, $\alpha_P = -0.68\pm0.1$, $\alpha_\delta = -0.35\pm0.3$,

$\alpha_\kappa = 1.4(1-\alpha_{Ip})\pm0.4$, $0<\alpha_{Ip}<0.7$ provides good fits (α_{Ip}=0.5 in above figure)

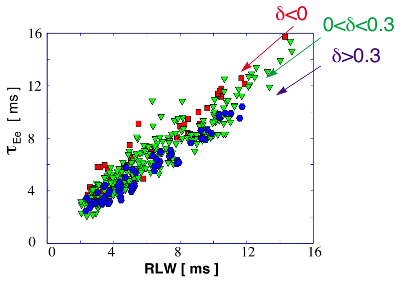
Comparison with ITER-98-L



- TCV ECRH heated (+ ohmic target) data fit quite well ITER-98-L-mode scaling

- The benefit of small (or negative) triangularity appears clearly (not included in ITER-98-L)

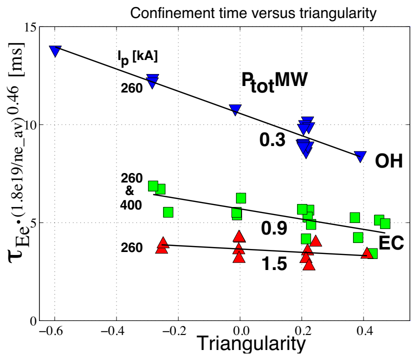
Comparison with Rebut-Lallia-Watkins



- ECRH and OH data well described by RLW scaling, based on a critical gradient transport model
- Negative δ appear also favourable in this representation, although RLW better integrates triangularity than ITER-98-L

Confinement versus Triangularity

- Triangularity range: $-0.6 < \delta < 0.45$
- 3 power classes
- density range: $1.3<n_{eo19}<3$
- confinement normalised using $\tau_{Ee} \sim (n_{e\_av})^{0.46}$ dependence
- P_{tot}/P_{OH} ~3 to 9 for q_{eng} = 2 to 3

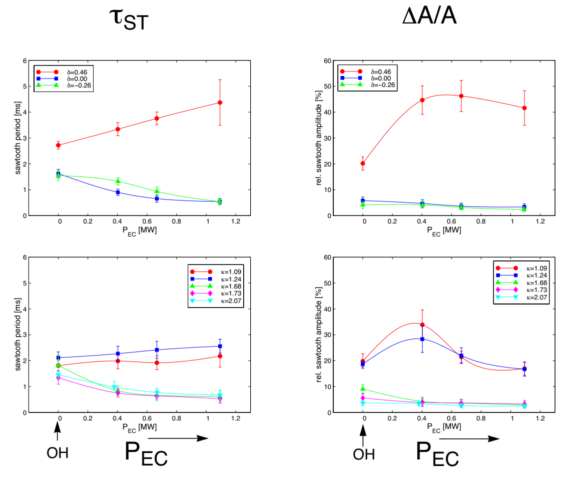


- The confinement time is larger at small or negative triangularities, particularly at low input power (OH).
- Power degradation may be weaker at positive triangularity, possibly reducing the triangularity dependence at high power
- Negative triangularities yield a higher τ/τ_{RLW} at all powers
- Higher power experiments with next gyrotron clusters (P_{tot} = 3 and 4.5 MW) will help clarify the situation

Sawteeth Stability vs Plasma Shape (elongation κ, triangularity δ)

δ - scan
κ = 1.5
$-0.3 < \delta < 0.5$

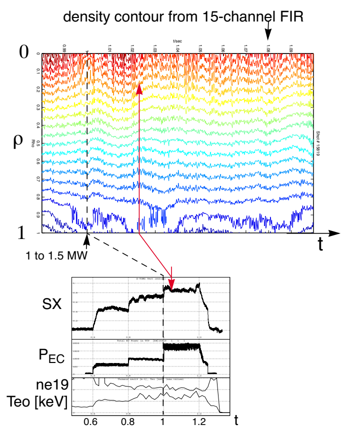
κ - scan
δ = 0.2
$1.1 < \kappa < 2.1$



- Low q_{eng} ~ 2 series, inversion radius ρ_{inv} ~ 0.55
- ρ_{inv} ~ constant throughout shape changes (5% variation)
- ECH power deposition inside inversion radius (TORAY)
- Increasing power at δ>0.3 or κ<1.6 stabilises sawteeth (increased period & amplitude)
- Increasing power at δ<0.2 or κ>1.6 destabilises sawteeth (reduced period & amplitude)
- Stabilisation found in experiment at positive triangularity in qualitative agreement with Mercier stability of internal kink & Resistive stability of m=1 mode:

  Ellipticity and negative triangularity are destabilising [Lütjens et al. NF 32 (1992) 1625]

Confinement Transitions with off-axis Heating



In the process of expanding the confinement database to decouple I_p and κ :

High q~20, κ=2 discharges have been heated off-axis at ρ~0.4 (HFS with B_φ=1.43T and 82.7 GHz)

At the highest EC powers, 1-1.5 MW
(P_{EC}/P_{OH} ~ 50-90 during EC, ~10-15 before EC),
spontaneous oscillating confinement transitions occur (the density profile flattens when the ϕ_{SX} drops)

In the different cases of counter-ECCD, confinement times about twice above RLW have been measured (10 keV)

Conclusions

- Confinement and central MHD studied varying triangularity (± δ), elongation (κ < 2.15)
  ECRH power < 1.5 MW, electron density, plasma current Ip
- General TCV ECRH scaling law close to ITER-L-98: shows the beneficial effect of δ < 0.2
- TCV ECRH data fit closely the critical gradient Rebut-Lallia-Watkins scaling
  (effect of δ less apparent then in ITER-L-98, but still visble)
- Triangularity dependence may be weaker at higher additional power (1.5 MW)
  - Higher EC power (3-4.5MW) will
    - clarify the issue of high power confinement triangularity dependence
    - and allow the study of high elongations (κ > 2) at significant P_{EC}/P_{OH}
- Shape dependence of sawtooth stability with central deposition
  in qualitative accord with Mercier and resistive stability of internal m=1 mode